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Fabrication of a Precision Mandrel for Replicating Wolter X-ray Optics

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FABRICATION OF A PRECISION MANDREL FOR REPLICATING WÖLTER X-RAY OPTICS

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1. Introduction

With the constant push to miniaturize existing technologies, there is an ever-increasing need to characterize smaller and smaller objects. X-rays have proven their usefulness for characterizing the internal structure of objects. However, standard x-ray imaging (i.e. projection radiography) methods are not ideally suited for high-resolution imaging of small objects. Lawrence Livermore National Laboratory is currently developing an x-ray microscope that uses high-efficiency reflective (Wölter Type I) optics for imaging millimeter-scale parts at resolutions of better than one micrometer. The optics use multilayer technology to increase the x-ray grazing angle, improving the efficiency of the optics.

The Wölter [1] imaging optic focuses x-rays that exit the sample (object plane) onto a scintillator (image plane). The scintillator converts the x-rays into visible light, which can be detected and imaged with a CCD camera. Our optic has a magnification of twelve. The distance between the sample and scintillator is five meters. Figure 1 shows the schematic of the microscope.

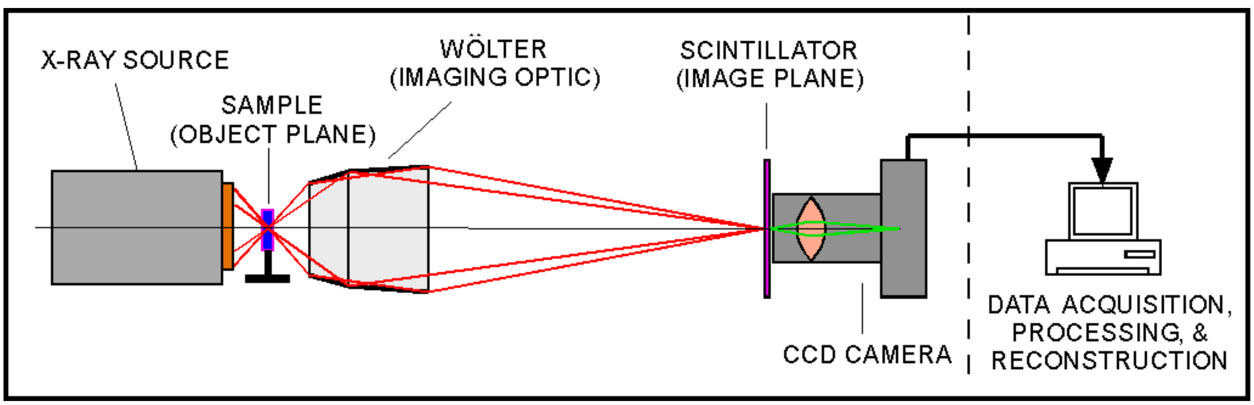
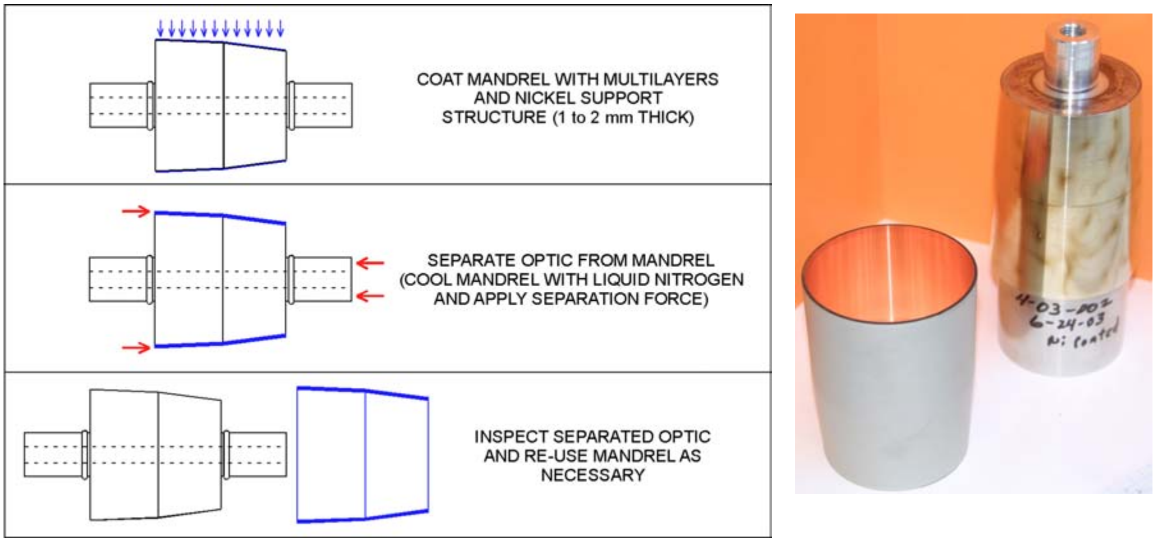


Figure 1: Schematic of our x-ray microscope

The Wölter optic consists of hyperbolic and elliptical reflective surfaces. This combination of reflective surfaces was first described by Wölter [1] in 1952. Although simple in concept, the fabrication of a high-quality imaging Wölter optic has proven to be difficult due to the tight tolerances on figure and roughness. In the remainder of this paper, we will describe the technique used to fabricate the optic and the challenges encountered.

2. Fabricating the Optic

To achieve the desired resolution, the optical design has very tight profile (figure) tolerances (~8 nanometers). Moreover, in order to achieve high efficiency, the surface roughness should be kept under 0.5 nanometers rms to minimize the scattering of x-rays. The optical surfaces on a Wölter optic are internal features. It is extremely difficult to machine and polish an external surface to our desired specifications; machining and polishing internal surfaces to our specifications is nearly impossible. Therefore, to meet imaging requirements, optical replication is being utilized.



(a) (b)

Figure 2: (a) replication procedure, (b) a replicated optic and its mandrel

The optical replication [2, 3, 4] method involves coating the outside surface of a high-accuracy super-polished mandrel and separating the coating (i.e. the optic) from the mandrel (see Figure 2). The coating consists of reflective multilayers and a 1.5-millimeter thick nickel substrate. The multilayers and nickel substrate are then separated from the mandrel. This process produces x-ray optics with similar figure and roughness properties to that of the high-accuracy mandrel.

X-ray optics are extremely sensitive to slope errors in the optical surface profile. Figure 3 shows the error created at the image plane by a slope error in one surface. The error, D, at the image plane is related to the slope error, □, at the mirror by the equation

$$D = L * 2 * \alpha$$

where L is the distance between the optical surface and the image plane. In our case, we do not want D to be greater than 6 micrometers; this corresponds to an error at the object plane of 0.5 micrometers (our microscope design has a magnification of 12x). The optical design process set L at 4583 millimeters. In our case we have two reflective surfaces, and each surface has an effect on D. Using an rms error analysis approach, we can combine the errors caused by both surfaces into a single equation:

$$D = \sqrt{(L * 2 * \alpha)^2 + (L * 2 * \alpha)^2} \quad \text{or} \quad D = \sqrt{2} * (L * 2 * \alpha)$$

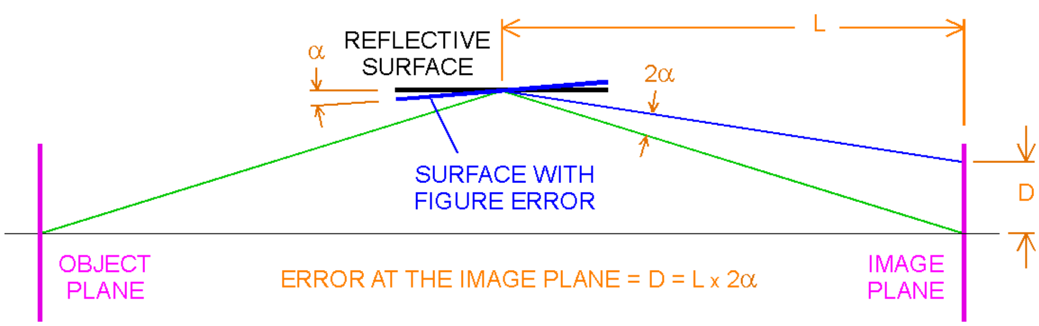
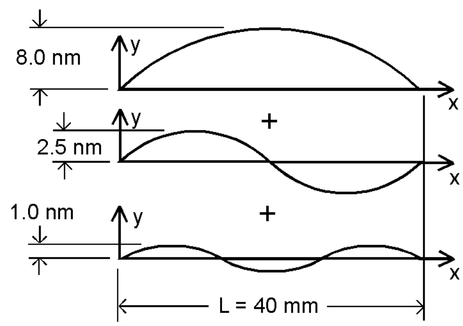


Figure 3: Relationship between figure error and image plane error

Rewriting the equation in terms of slope error, we get

$$\alpha = \frac{D}{2\sqrt{2} * L}$$

Using this equation, we get a slope error, □, due to figure errors only of 0.463 micro-radians or 0.10 arc-seconds. A 0.463 micro-radian slope error corresponds to an error in the surface profile of approximately eight nanometers. The eight-nanometer tolerance applies to higher order errors as shown in Figure 4; effects from size and linear slope errors over each surface are not as critical because these errors can nearly be corrected by moving the image plane towards or away from its designed position.



$$y_{ij} = 8\sin\left(\frac{\pi x}{L}\right) + 2.5\sin\left(\frac{2\pi x}{L} + 2\pi\frac{i}{10}\right) + \sin\left(\frac{3\pi x}{L} + 2\pi\frac{j}{10}\right)$$

Let b_{ij} = the blur diameter caused by curve y_{ij}

$$b_{ave} = \frac{\sum_{i=0}^{9}\sum_{j=0}^{9} b_{ij}}{100} = 1.0 \text{ micrometer}$$

Figure 4: 8-nanometer errors in the profile can cause 1-micrometer imaging errors

3. Fabricating the Mandrel

Fabrication of the mandrel requires several steps: rough cutting the mandrel out of aluminum, nickel-plating the surface, diamond-turning the desired profile, and, finally, super-polishing the surface to a roughness under 0.5 nanometers rms. The diamond turning was done on LLNL's PERL II diamond turning machine (see Figure 5).

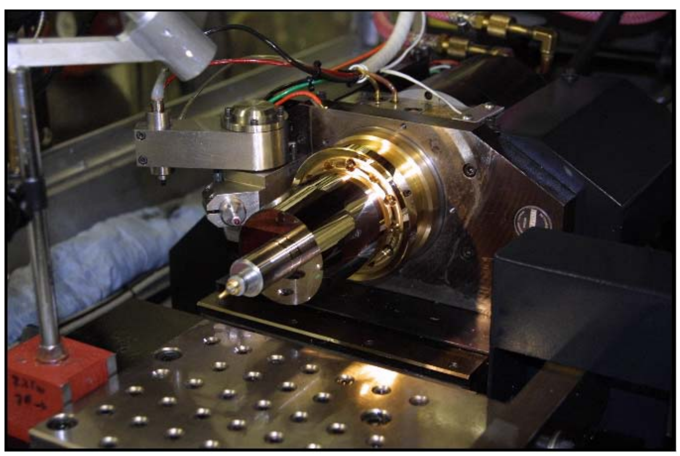


Figure 5: Diamond turning the mandrel

The size of the mandrel will be measured on the LODTM (Large Optic Diamond Turning Machine) in the future. The profile of each surface was measured with a Fizeau interferometer. The measured profiles deviated from the desired profiles by approximately 100 nanometers, which is an order of magnitude above what we want. We are currently diamond turning a second mandrel on the LODTM to improve the performance of this step.

Our first mandrel is currently being super-polished by an outside vendor. Getting the 0.5-nanometer roughness is going to take considerable effort. We currently are getting roughness measurements of between 0.6 and 1.5 nanometers rms. Moreover, some of the polishing compound is getting embedded in the surface, which could cause problems during the replication process. We are confident that these issues will be resolved in the near future. Figure 6 shows an Atomic Force Microscope (AFM) measurement of the hyperbola.

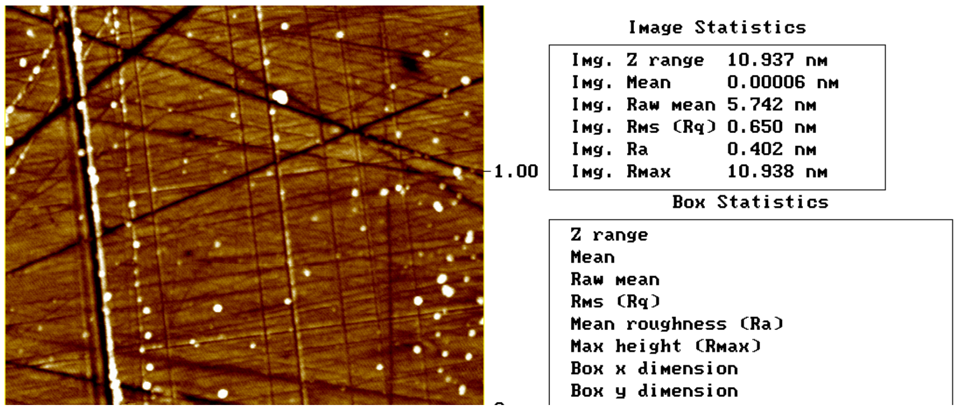


Figure 6: AFM roughness measurement of the hyperbola

4. Conclusion

Machining and polishing the mandrel to the desired tolerances is difficult. Also, limitations in techniques for measuring the mandrel dimensions are making it difficult to verify the results of the manufacturing processes. We will be investigating methods and tools for addressing our fabrication and metrology limitations. Regardless, we will be producing a replicated optic soon, and we will be building the prototype x-ray microscope in the spring of 2004 (see Figure 7). We will incorporate new optics into the microscope as the mandrel fabrication processes and optics improve.

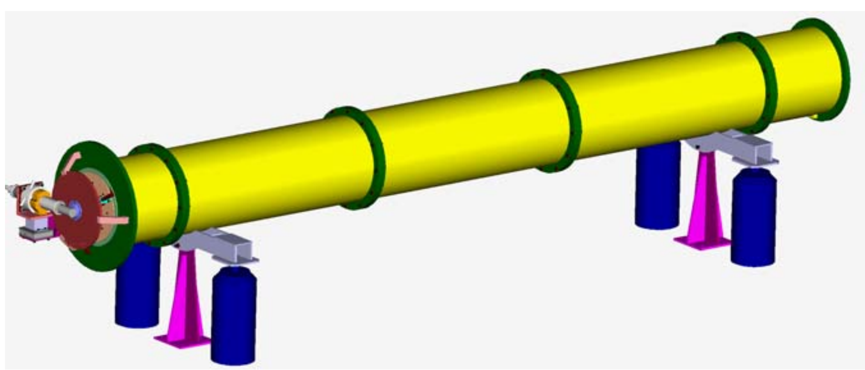


Figure 7: 3-D CAD model of the x-ray microscope

5. References

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